HADRONIC CENTRALITY DEPENDENCE IN NUCLEAR COLLISIONS

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The kaon number density in nucleus+nucleus and p+p reactions is investigated for the first time as a function of the initial energy density ϵ and is found to exhibit a discontinuity around ϵ=1.3 GeV/fm^3. This suggests a higher degree of chemical equilibrium for $\epsilon > 1.3$ GeV/fm^3. It can also be interpreted as reflection of the same discontinuity, appearing in the chemical freeze out temperature (T) as a function of ϵ. The $N^{\alpha \sim 1}$ dependence of (u,d,s) hadrons, with N the number of participating nucleons, also indicates a high degree of chemical equilibrium and T saturation, reached at ϵ >1.3 GeV/fm^3. Assuming that the intermediate mass region (IMR) dimuon enhancement seen by NA50 is due to open charm ($D\overline{D}$), the following observation can be made: a) Charm is not equilibrated. b) $J/\Psi/D\overline{D}$ suppression -unlike $J/\Psi/DY$- appears also in S+A collisions, above $\epsilon \sim$1 GeV/fm^3. c) Both charm and strangeness show a discontinuity near the same ϵ. d) J/Ψ could be formed mainly through $c\overline{c}$ coalescence. e) The enhancement factors of hadrons with u,d,s,c quarks may be connected in a simple way to the mass gain of these particles if they are produced out of a quark gluon plasma (QGP). We discuss these results as possible evidence for the QCD phase transition occuring near $\epsilon \sim$1.3 GeV/fm^3.

1 Introduction

The quark-gluon plasma phase transition predicted by QCD [3] may occur and manifest itself in ultrarelativistic nuclear collisions through discontinuities in the initial energy density (ϵ_i) dependence of relevant observables. A major example of a discontinuity is seen in the $J/\Psi/DY$ [4] discussed e.g. in [5,6]. We investigate for the first time the dependence of strangeness production, in particular of kaons, on the initial energy density ϵ_i [11,10]. The degree of equilibrium achieved in nuclear collisions has been intensively studied comparing hadron ratios and densities to models (see e.g. [6,7,8,9]). We investigate here if chemical equilibrium is achieved, examining an other aspect of equilibrium states, namely the volume (V) independence of hadron densities (ρ).[a]

2 Results and discussion

The kaon density (ρ_K=(K per collision)/V) at the thermal freeze out in nuclear reactions, investigated as a function of the initial energy density ϵ_i (figure 1) (see [10] for calculation details), exhibits a dramatic changeover around ϵ=1.3 GeV/fm^3, saturating for higher ϵ values, while it is falling below. The syst. error on ϵ_i is estimated to be $\sim$ 30%. It is assumed that the number of nucleons participating in the collision (N) is proportional to the volume of the particle source at the thermal freeze out [10]. The new results from Si+Au at 14.6 A GeV and p+p at 158 A GeV shown in figure 1, which are not included in [10], have been estimated using data from [12] and methods described in [10]. Furthermore, ρ_K rises with N respectively with V below ϵ=1.3 GeV/fm^3 while it does not depend on N respectively on V above ϵ=1.3 GeV/fm^3. To illustrate this, two values of V are noted on figure 1. The changes of $K^\pm$ and $\pi^\pm$ with N within the Pb+Pb system, have been first realized in [13]. A similar behaviour as the one seen in figure 1, can be inferred for pions as well as for the K/π ratio (S.K. work in progress).

The N^α exponent of hadrons with (u,d,s) quarks above ϵ=1.3 GeV/fm^3, do not depend on the particle mass (figure 3). At ϵ >1.3 GeV/fm^3 α is near to one, as expected in case of a chemically equilibrated state, assuming

[a] Results of the NA52 experiment shown in this talk can be found in [1,2].

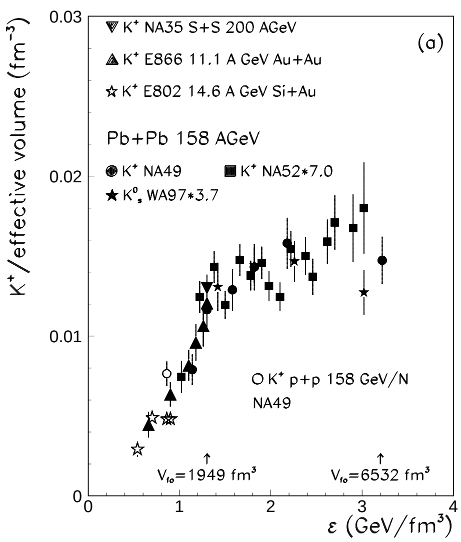

Figure 1. Initial energy density (ϵ) dependence of the K^+ multiplicity over the effective volume of the particle source at thermal freeze out [10].

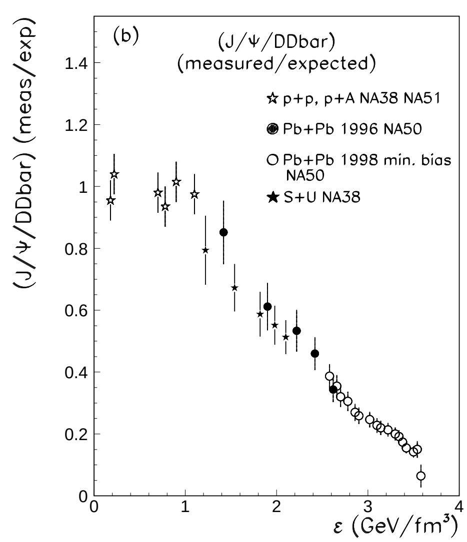

Figure 2. Initial energy density (ϵ) dependence of the $J/\Psi/D\overline{D}$ (measured/'expected') ratio [10].

N $\sim$ V. The deviations seen in ϕ, π^0 and $\overline{p}$ may be due to the transverse momentum acceptance. Therefore, figure 3 supports the assumption of a high degree of chemical equilibrium reached above ϵ=1.3 GeV/fm^3, among hadrons with u,d,s quarks. The N^α exponent of kaons is found to depend strongly on $\sqrt{s}$ for kaons (figure 4). Therefore, below ϵ=1.3 GeV/fm^3, ρ_k (figure 1 and figure 4), ρ_π and the K/π ratio, show an increase with increasing N respectively with V.

Figures 1, 3 and 4 can be interpreted in two ways. Firstly, kaons may achieve a higher degree of chemical equilibrium only for $\epsilon > 1.3$ GeV/fm^3, and may not be fully equilibrated below [10]. The equilibration of strangeness is expected in a QGP and its observation at $\epsilon \sim 1.3$ GeV/fm^3 could therefore be a sign of a transition to QGP. In this case, it is a transition from a non equilibrated hadron gas to an equilibrated QGP. It is therefore not a well defined phase transition in the thermodynamic sense.

Secondly, kaons can be in fact chemically equilibrated also below ϵ= 1.3 GeV/fm^3, and the change respectively the constancy of ρ_K with V_{fo} and ϵ_i observed in figure 1, can be a result of the increase of the freeze out temperature with ϵ_i below ϵ= 1.3 GeV/fm^3, respectively of the stability of T_{fo} above 1.3 GeV/fm^3. This dependence of T_{fo} on ϵ_i, namely rising until it reaches a critical T_c value and saturating above for all reactions, would strongly support the QCD phase transition appearing at $\epsilon \sim 1.3$ GeV/fm^3. This interpretation fully agrees with thermal models which suggest that particle ratios at freeze out are compatible with thermalization even in A+A collisions at 1 A GeV [7]. However the first interpretation is not in gross disagreement with [7], because there the thermal model description is modified (introducing e.g. $\rho_k \sim V$) in order to describe the data at 1 A GeV.
Furthermore, the correct interpretation can be corroborated by further investigations discussed in the following. The nonzero baryochemical potential (μ_B), which in the reactions shown in figure 1, happens to change with ϵ_i, makes the intepretation of figure 1 difficult. Therefore, it appears that the dependence of the temperature at chemical

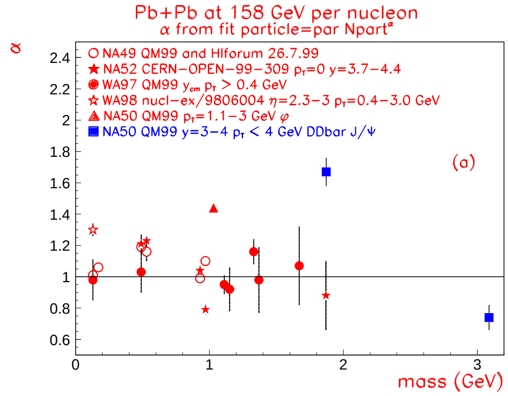

Figure 3. The parameter α, resulting from the N^{α} fit to hadron yields shown as a function of the mass of the particles in the region ϵ >1.3GeV/fm^3 at SPS. N is the number of participating nucleons.

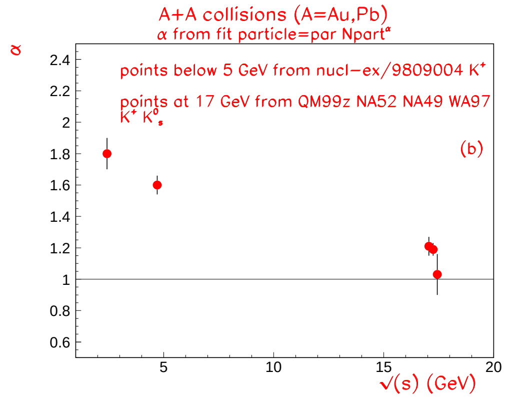

Figure 4. The parameter α, resulting from the N^{α} fit to hadron yields shown as a function of $\sqrt{s}$ for kaons. N is the number of participating nucleons.

freeze out extrapolated to μ_b=0, on ϵ_i, would help to identify and prove the QCD phase transition. A rising and then a for ever saturating freeze out temperature above ϵ 1.3 GeV/fm^3 is a strong argument that the QCD phase transition occurs at this ϵ, and figure 1 is a direct consequence of it.

The question if the QCD phase transition appears at the critical ϵ_i in any volume, or if there is additionally a critical initial volume of the particle source above which the transition takes place, can be answered comparing QGP signatures in systems with different volumes but the same ϵ_i. For example comparing $p+p$, e^+e^- etc collisions to heavy ion collisions e.g. at the same ϵ. This is not yet done for the signature of the J/Ψ suppression and it has to be clarified e.g. using Tevatron data [10]. For the signature of strangeness enhancement it is suggested by figure 1 in [8] that there is indeed a critical initial volume, only above which strangeness is enhanced over $p+\overline{p}$ *at the same* ϵ_i. This conclusion follows, if we assume that Tevatron reaches at least ϵ_i values similar to SPS A+A collisions [14] and if figure 1 in [8] is not biased by the model calculation [8].

If strangeness is indeed not equilibrated at ϵ < 1.3 GeV/fm^3, this may explain the decrease of the double ratio (K/π)(A+A/p+p) with increasing $\sqrt{s}$. In particular, a larger strangeness annihilation is enforced by equilibrium at SPS reducing the strange particle yield. However the assumption of non equilibrium of $s\overline{s}$ at low ϵ is not nessecary here, since the above observation can be possibly traced back to e.g. the variation of $\mu_B(A+A)/\mu_B(p+p)$ with $\sqrt{s}$ in A+A collisions. Furthermore, in the context of QGP formation, it seems irrelevant to discuss e.g. $s\overline{s}$ enhancement in A+B over p+p collisions in a nonequilibrium situation. It is the very establishment of equilibrium in the (u,d,s) sector, which can reveal informations on QGP.

The kaon number densities in p+p and A+B collisions in figure 1 are similar, when compared at the same ϵ_i. See also [15] for a discussion of universality of pion phase space densities.

Our prediction for the N dependence of hadrons at RHIC and LHC is the N^1 thermal limit, as long as hadron yields are domminated by low transverse momentum particles. Furthermore, if the changeover of ρ_k at ϵ =1.3 GeV/fm^3 shown in figure 1 is due to the QCD phase transition, we predict for RHIC and LHC the same total strangeness (or kaon) number density and the same freeze out temperature, -after correction for the

μ_B dependence-, as for ϵ =1.3-3.0 GeV/fm^3. If this change is however due to the onset of equilibrium in a hadronic gas, and the QCD phase transition takes place at higher ϵ, it may manifest itself through a second changeover of hadron number densities, ratios and freeze out temperatures -after correction for the different μ_B- e.g. in RHIC above $\epsilon \sim 3$ GeV/fm^3.

Assuming that the IMR dimuon enhancement seen by NA50 is due to open charm, the following observations can be made: a) open charm appears not to be equilibrated ($\alpha = 1.7$) (figure 3) [10]. b) The $J/\Psi/D\overline{D}$ ratio deviates from p+p and p+A data also in S+U collisions (figure 2), above ϵ ~1 GeV/fm^3. c) It therefore appears that both charm and strangeness show a discontinuity near the same ϵ~1 GeV/fm^3 [10], similar to the critical ϵ_c ~1-2 GeV/fm^3 predicted by QCD [3,5]. d) The N dependence of the $J/\Psi/D\overline{D}$ ratio can be interpreted as the J/Ψ being formed through $c, \overline{c}$ coalescence [10].

e) Finally, the enhancement factors of hadrons with u,d,s,c quarks may be connected in a simple way to the mass gain of these particles in the quark gluon plasma (table below) [16]. T_q are the enhancement factors of the lightest mesons with u,d,s,c quarks (π, K, D), if they are produced out of a quark gluon plasma (e.g. $g+g \rightarrow s+\overline{s}$ (1)), as compared to their direct production from hadron interactions away from the transition point (e.g. $p+p \rightarrow K^+ + \Lambda + p$ (2)). The gain is taken proportional to $m_{particle} - m_{quarks}$, as this expresses the different thresholds of reactions (1) and (2). In the table below the predicted enhancement factors (T_q) of hadrons with u,d,s,c quarks from a QGP are compared to the experimentally measured ones (E_q), and are found to be similar. (Definitions: $th_q = m_0 - m_q$, $m_{u,d}$=7 MeV, m_s=175 MeV, m_c=1.25 GeV, $m_0 = m(\pi, K, D)$, $T_q = \sqrt{th_q/th_{u,d}}$, $E = \frac{(A+B)}{(N+N)}$, $E_q = E/E_{u,d}$).

q	th_q	T_q	E	E_q
u,d	133	1	$\pi/N \sim 1.12$	1
s	320	1.55	$K/N \sim 2$	1.79
c	615	2.15	$D\overline{D} \sim 3$	2.68

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